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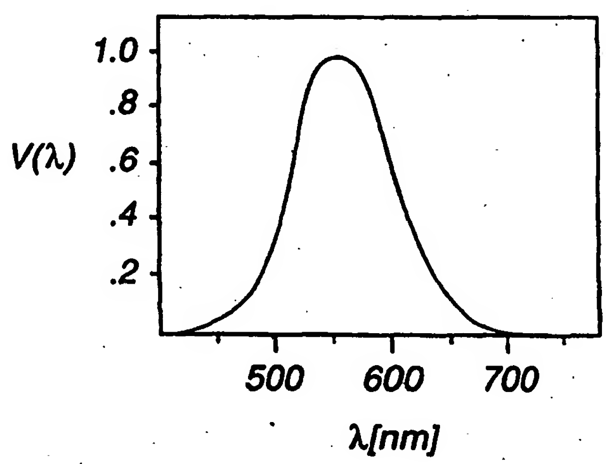
(54) Title: LIGHT EMITTING DEVICE WITH PHOSPHOR HAVING HIGH LUMINOUS EFFICACY

(57) Abstract

A lamp comprises a light emitting element such as a light emitting diode or a laser diode which emits blue light, and a phosphor composition which absorbs the blue light having a first spectrum from the light emitting element and emits light having a second spectrum. The phosphor composition comprises at least one of $Ba_2MgSi_2O_7:Eu^{2+}$; $Ba_2SiO_4:Eu^{2+}$; and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$. The invention also relates to a light emitting element which emits blue light, and a phosphor composition which absorbs the blue light from the light emitting element having a first spectrum and emits light having a second spectrum, wherein the spectral luminous efficacy of light emitted by the lamp is at least 550 lumens per watt. The high spectral luminous efficacy of the output spectrum efficiently converts the power input to the lamp into lumens to provide a high brightness. For example the device luminous efficacy of the lamp can be 35–45 lumens output per watt of input electric power or more.



aluminum gallium nitride (AlGaN) layer 50, a p-type GaN layer 60, a positive contact 70, and a negative contact 80. The various semiconductor layers 30, 40, 50, and 60 are typically deposited on one another by chemical vapor deposition (CVD). In general, each layer may comprise $In_xGa_yAl_{(1-x-y)}N$, where $0 \le x \le 1$ and $0 \le y \le 1$. Although an LED is shown in Figure 3 as an example, the invention encompasses other light emitting devices such as laser diodes. In addition, semiconductor materials other than the GaN system can be used, such as gallium arsenide (GaAs) and its alloys, silicon, and silicon carbide (SiC).

Other examples of LEDs and laser diodes which emit in the blue wavelengths are known in the art. See, for example, U. S. Patent Nos. 5,813,753; 5,813,752; 5,338,944; 5,416,342; 5,604,763; and 5,644,584. LEDs and laser diodes which emit blue and UV radiation are also described in Shuji Nakamura and Gerhard Fasol, "The Blue Laser Diode" (1997).

Figure 4 illustrates a lighting apparatus according to an exemplary embodiment of the invention. The lighting apparatus 200 includes a light source 210 which may be an LED or a laser diode, for example, powered by leads 212, 214. The light source 210 and a portion of the leads 212, 214 are encapsulated within a transmissive body 220 which may comprise a silicone, glass, or plastic material, for example.

The phosphor composition 230 may be formed on an outer surface of the transmissive body 230, as shown in Figure 4, or directly on the light source 210 within the transmissive body 230. To apply the phosphor composition to the transmissive body 230 or light source 210, the phosphor composition may be added to a liquid suspension medium, such as the nitrocellulose/butyl acetate binder and solvent solution used in commercial lacquers. Many other liquids including water with a suitable dispersant and thickener or binder, such as polyethylene oxide, can be used. The phosphor-containing suspension is painted or coated or otherwise applied on the LED and dried. The lighting apparatus 200 may also include a plurality of scattering particles, such as

titanium dioxide (TiO_2) or aluminum oxide (Al_2O_3) particles, embedded in the transmissive body 230, for example if a laser diode is used as the light source 210.

Upon application of a current to the leads 212, 214, the LED produces a blue light which is converted by the phosphor composition 230 to green light. The blue light emitted by the LED or laser diode can efficiently excite the green-emitting phosphors. According to exemplary embodiments of the invention, one or more of the following phosphors are used: $Ba_2MgSi_2O_7:Eu^{2+}$; $Ba_2SiO_4:Eu^{2+}$; and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$.

In the above phosphors, the element following the colon represents an activator. The notation (A,B,C) signifies (A_x,B_y,C_z) where $0 \le x \le 1$ and $0 \le y \le 1$ and $0 \le z \le 1$ and $x+y+z=1$. For example, (Sr,Ca,Ba) signifies (Sr_x,Ca_y,Ba_z) where $0 \le x \le 1$ and $0 \le y \le 1$ and $0 \le z \le 1$ and $x+y+z=1$. Typically, x, y, and z are all nonzero. The notation (A,B) signifies (A_x,B_y) where $0 \le x \le 1$ and $0 \le y \le 1$ and $x+y=1$. Typically, x and y are both nonzero.

The green emitting phosphors preferably have peak emissions between about 500 nm and about 555 nm. Figures 5, 6, and 7 show the emission spectra for the three green phosphors disclosed herein. As shown in the Figures, the emission spectra of the green phosphors coincide to a large extent with the most sensitive region of the spectral luminous efficacy curve of Figure 1. For example, $Ba_2MgSi_2O_7:Eu^{2+}$ has a peak emission at about 495-505 nm, typically about 500 nm, $Ba_2SiO_4:Eu^{2+}$ has a peak emission at about 500-510 nm, typically about 505 nm, and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$ has a peak emission at about 535-545 nm, typically about 540 nm. The resulting spectral luminous efficacy of the lamp using one or more of these phosphors, assuming substantially all of the blue light is absorbed by the phosphor, is typically greater than 550 lumens per watt of radiant power.

Another variable which is commonly used to describe the effectiveness of a lamp at generating lumens is the device luminous efficacy, defined as the

luminous flux output by the lamp divided by the electric power input to the lamp. The device luminous efficacy of the lamp takes into account the spectral luminous efficacy of the output spectrum as well as three additional factors. First, the device efficiency represents the radiant power output by the LED divided by the electric power input to the LED. For a typical blue LED, the device efficiency is about 10%. Second, the quantum efficiency of the phosphor represents a loss associated with the transfer of energy from the absorbed photons to the emitted photons. The quantum efficiency is defined as the number of photons emitted by the phosphor divided by the number of photons absorbed by the phosphor. For the phosphors described herein, the quantum efficiency is typically about 80%. Third, there is an energy loss associated with the decrease in frequency of the emitted light affected by the phosphor equal to $h\Delta v$, where h is Plank's constant and Δv is the change in frequency of the light. For light absorbed at 450 nm and emitted at 555 nm, the emitted energy is 450/555 = 81% of the absorbed energy.

Taking into account all of these factors, the device luminous efficacy (DLE) for a typical lamp is:

$$DLE = (DE)*(QE)*(FL)*(SLE)$$

where DE = device efficiency, QE = phosphor quantum efficiency, FL = frequency loss efficiency, and SLE = spectral luminous efficacy. For a typical lamp according to exemplary embodiments of the invention, the device luminous efficacy is (10%) * (80%) * (81%) * (550 to 683 lumens per watt of radiant power) = about 35-45 lumens per watt of input electric power. This range of device luminous efficacy represents a significant increase over known LED lamps. For example, conventional green-emitting LEDs typically produce no more than 30 lumens per watt (lpw) of input electric power.

According to another embodiment of the invention, the device luminous efficacy can be increased still further by utilizing a laser diode, which may have a device efficiency of 40%, for example. Assuming the other variables remain substantially the same, the device luminous efficacy is increased to about 143-177 lumens per watt of input electric power.

Using either the LED or the laser diode as a light source, the output light has a spectrum which is concentrated around the most sensitive region of the spectral luminous efficiency curve of Figure 1, producing a high spectral luminous efficacy, e.g. at least 550 lpw. The invention thus provides the advantage of a significantly increased luminous flux output without any increase in the electric power input to the LED or laser diode.

Other embodiments of the invention will be apparent to those skilled in the art from a consideration of this specification or practice of the invention disclosed herein. It is intended that the specification and examples be considered as exemplary only, with the true scope and spirit of the invention being defined by the following claims.

WHAT IS CLAIMED IS:

1. A lamp comprising:

a light emitting element which emits blue light; and

a phosphor composition which absorbs the blue light having a first spectrum from the light emitting element and emits light having a second spectrum, the phosphor composition comprising at least one of $Ba_2MgSi_2O_7:Eu^{2+}$; $Ba_2SiO_4:Eu^{2+}$; and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$.

2. The lamp of claim 1, wherein the light emitting element comprises a light emitting diode.

3. The lamp of claim 1, wherein the light emitting element comprises a laser diode.

4. The lamp of claim 1, wherein the second spectrum has a spectral luminous efficacy of at least 550 lumens per watt of radiant power.

5. The lamp of claim 1, wherein the lamp has a device luminous efficacy of at least 35 lumens per watt of input electric power.

6. The lamp of claim 1, wherein the blue light has an emission peak at a wavelength greater than 400 nm and less than 520 nm.

7. The lamp of claim 1, wherein the blue light has an emission peak between about 450 nm and about 470 nm.

8. The lamp of claim 1, wherein the second spectrum has an emission peak between about 500 nm and 570 nm.

9. The lamp of claim 1, further comprising a transmissive body which encapsulates the light emitting element, wherein the phosphor composition is deposited on a surface of the transmissive body.

10. A lamp comprising:

a light emitting element which emits blue light; and

a phosphor composition which absorbs the blue light from the light emitting element having a first spectrum and emits light having a second spectrum, wherein the spectral luminous efficacy of light emitted by the lamp is at least 550 lumens per watt.

11. The lamp of claim 10, wherein the light emitting element comprises an LED.

12. The lamp of claim 10, wherein the lamp has a device luminous efficacy of at least 35 lumens per watt of input electric power.

13. The lamp of claim 10, wherein the light emitting element comprises a laser diode.

14. The lamp of claim 10, wherein the second spectrum has an emission peak between about 535 and 545 nm.

15. The lamp of claim 10, wherein the second spectrum has an emission peak between about 495 and 505 nm.

16. The lamp of claim 10, wherein the second spectrum has an emission peak between about 500 and 510 nm.

17. The lamp of claim 10, wherein the phosphor composition comprises at least one of: $Ba_2MgSi_2O_7:Eu^{2+}$; $Ba_2SiO_4:Eu^{2+}$; and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$.

18. A lamp comprising:

a light emitting element which emits blue light; and

a phosphor composition which absorbs the blue light from the light emitting element having a first spectrum and emits light having a second spectrum, wherein the device luminous efficacy of the lamp is at least 35 lumens per watt.

19. The lamp of claim 18, wherein the spectral luminous efficacy of light emitted by the lamp is at least 550 lumens per watt.

20. A method of producing light comprising the steps of:

generating blue light with a light emitting device;

directing the blue light to a phosphor composition which absorbs the blue light, the phosphor composition comprising at least one of: $Ba_2MgSi_2O_7:Eu^{2+}$; $Ba_2SiO_4:Eu^{2+}$; and $(Sr,Ca,Ba)(Al,Ga)_2S_4:Eu^{2+}$; and

converting the blue light with the phosphor composition to light having a different spectrum.

21. The method of claim 20, wherein the step of generating blue light comprises generating blue light with a light emitting diode.

22. The method of claim 21, wherein the phosphor composition converts the blue light to light having a spectral luminous efficacy of at least 550 lumens per watt of radiated power.

23. A method of producing light comprising the steps of:

generating blue light with a light emitting device; and

absorbing the blue light with a phosphor composition which emits light of a different spectrum such that the light emitted by the light emitting device and phosphor composition together has a spectral luminous efficacy of at least 550 lumens per watt of radiated power.

FIG. 1

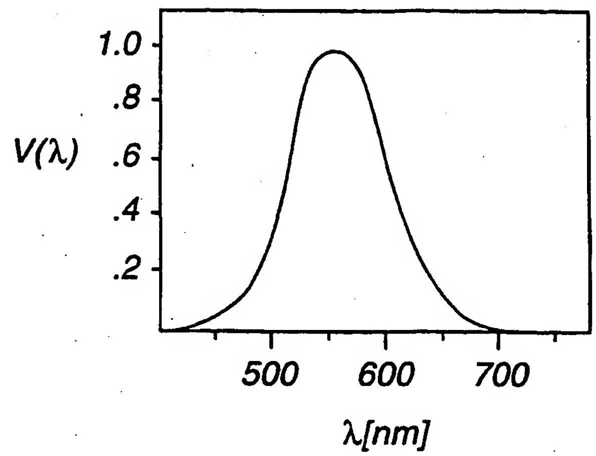

1.0
.8
V(λ)
.6
.4
.2
500
600
700
λ[nm]

FIG. 2

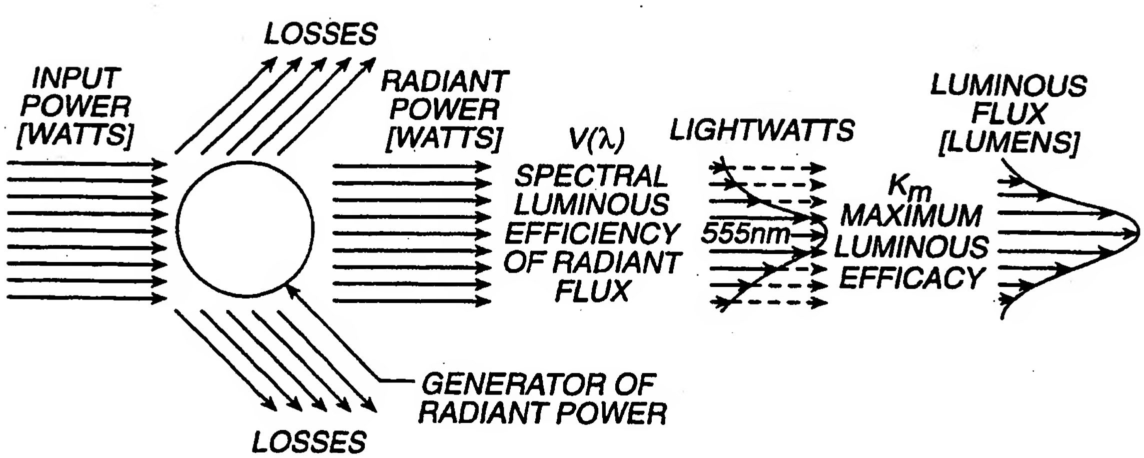

LOSSES
INPUT POWER [WATTS]
RADIANT POWER [WATTS]
V(λ) SPECTRAL LUMINOUS EFFICIENCY OF RADIANT FLUX
LIGHTWATTS
555nm
Km MAXIMUM LUMINOUS EFFICACY
LUMINOUS FLUX [LUMENS]
GENERATOR OF RADIANT POWER
LOSSES

FIG. 3

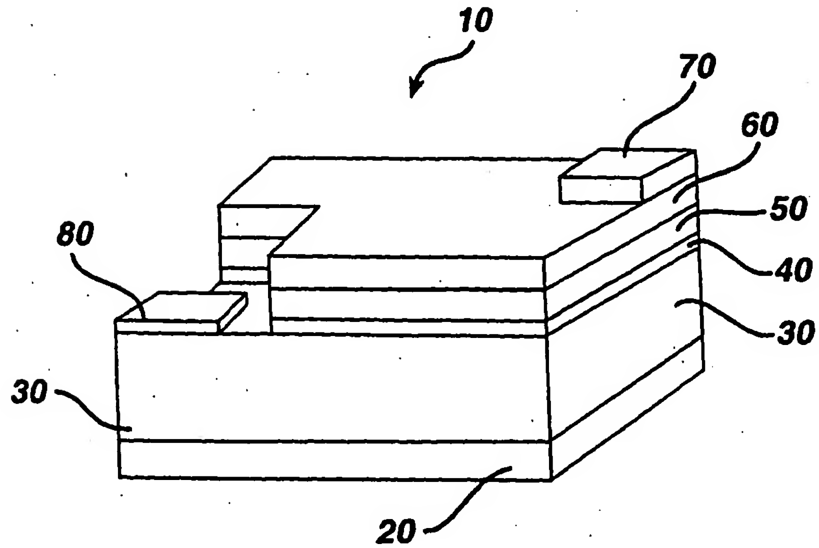


FIG. 4

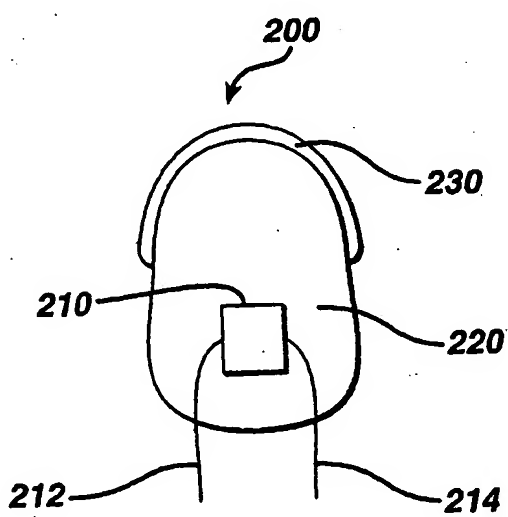


FIG. 5

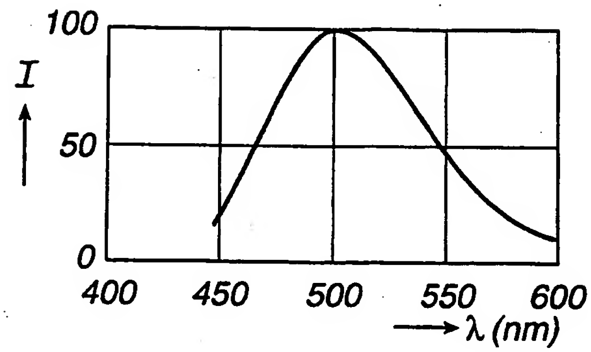


FIG. 6

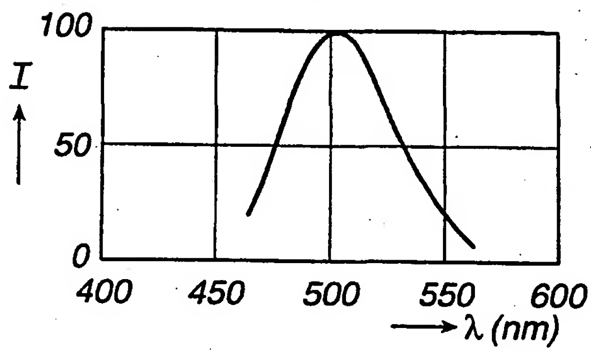
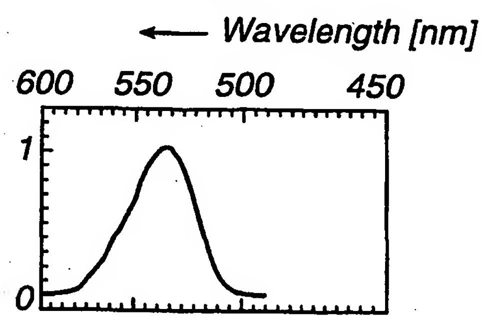


FIG. 7



INTERNATIONAL SEARCH REPORT

Inte onal Application No
PCT/US 99/28279

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01L33/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	WO 98 19290 A (TEWS HELMUT ;AVERBECK ROBERT (DE); SIEMENS AG (DE)) 7 May 1998 (1998-05-07) page 3, line 8 -page 4, line 4	1-3,6,7, 10,11, 13,17, 18,20, 21,23
A	DE 196 38 667 A (SIEMENS AG) 2 April 1998 (1998-04-02) claims 1,4	1-3,6,7, 9-11,13, 17,18, 20,21,23

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
3 April 2000	10/04/2000
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer De Laere, A

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INTERNATIONAL SEARCH REPORT

Inte. onal Application No
PCT/US 99/28279

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	POORT S H M ET AL: "Optical properties of Eu-activated orthosilicates and orthophosphates" JOURNAL OF ALLOYS AND COMPOUNDS, CH, ELSEVIER SEQUOIA, LAUSANNE, vol. 260, no. 1, 12 September 1997 (1997-09-12), pages 93-97, XP004094706 ISSN: 0925-8388 figure 1	1,8,10, 15-17,20
A	LE THI K T ET AL: "INVESTIGATION OF THE MS-AL2S3 SYSTEMS (M=CA, SR, BA) AND LUMINESCENCE PROPERTIES OF EUROPIUM-DOPED THIOALUMINATES" MATERIALS SCIENCE AND ENGINEERING B, CH, ELSEVIER SEQUOIA, LAUSANNE, vol. B14, no. 4, 1 September 1992 (1992-09-01), pages 393-397, XP000359265 ISSN: 0921-5107 figures	1,8,10, 15,17,20
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